Public

EUV computational lithography to enable technology scaling below 10 nm

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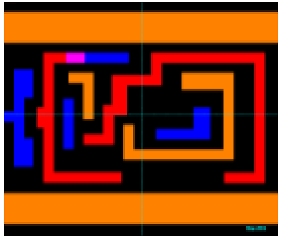
Agenda

- Introduction: Need for EUVL for sub-10 nm node
- Modeling challenges for EUV specific effects
- FlexPupil and Source-mask optimization (SMO)
- EUV sub-resolution assist features (SRAF)
- Full field OPC and verification
- Summary

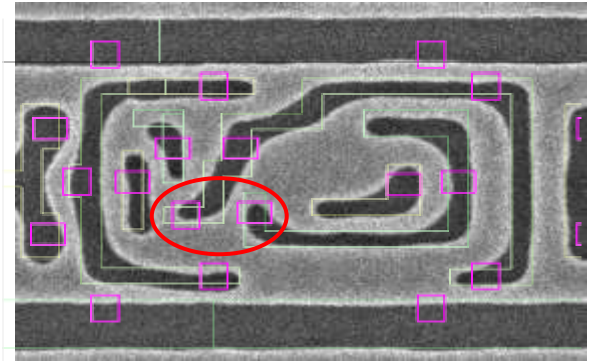
EUV improves post etch pattern fidelity vs.ArFi LE^3

NXE:3300 & Tachyon NXE OPC+ mask single exposure example

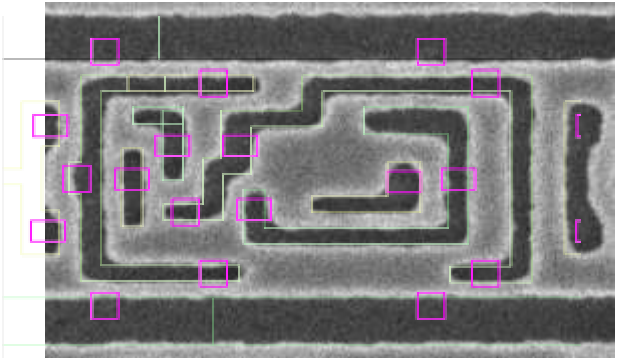
- 10 nm node logic 2D M1 evaluated in ASML-IMEC ‘Scaling project’
- SEMs show improved pattern fidelity & contact coverage for EUV vs. ArFi LE^3



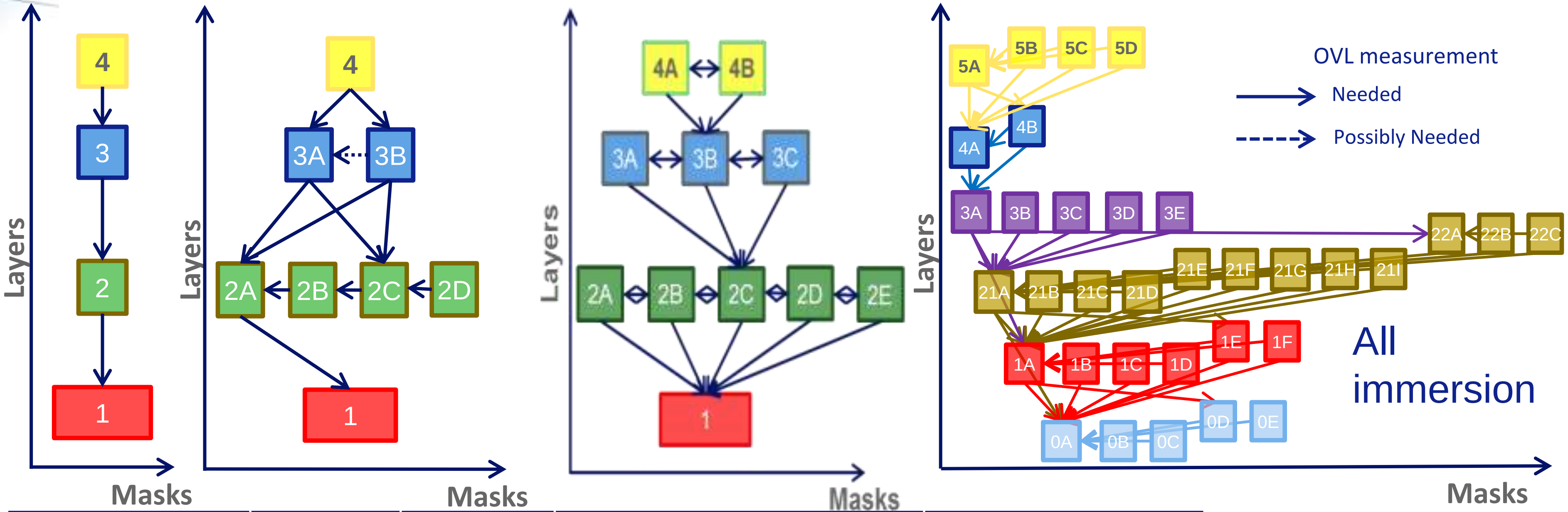
ArFi LE^3 wafer
after TiN etch



EUV single exposure wafer
after TiN etch



Multi-patterning cost & complexity drive need for EUV



Node	28nm	20nm	10nm	7 nm all immersion
# of lithography steps	4	8	11	33
# OVL metrology	4	10-11	14-17	?
Max metrology / litho steps	1	2	3	3

Multi-patterning cost & complexity drive need for EUV

ASML

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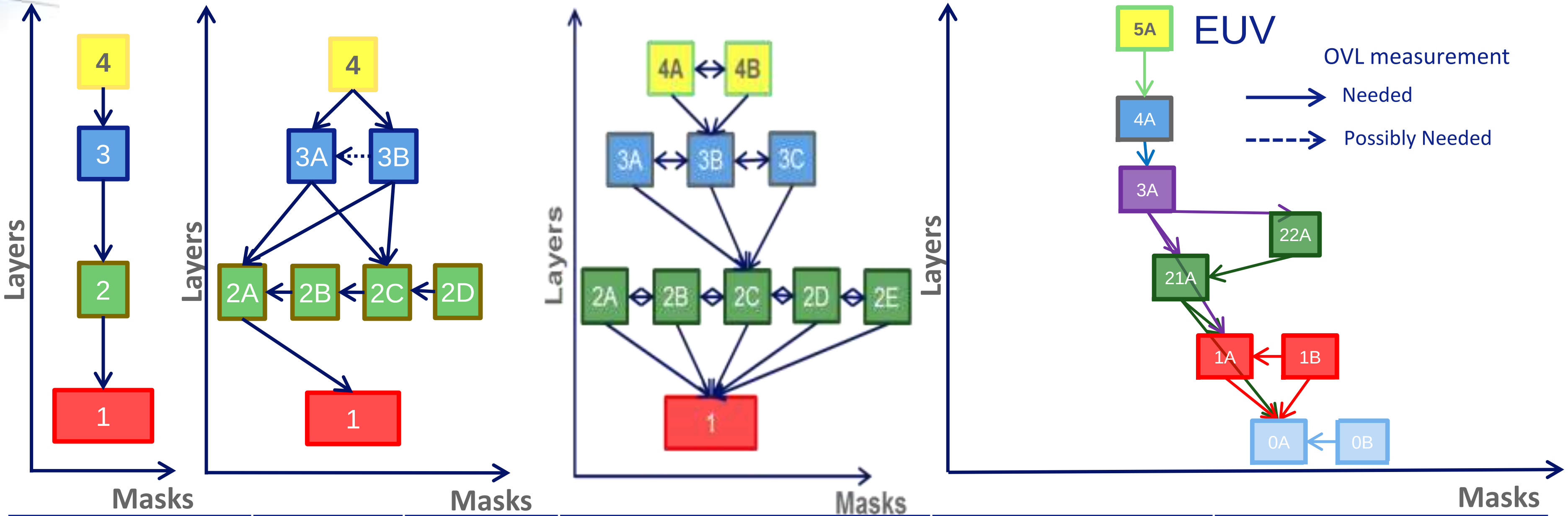
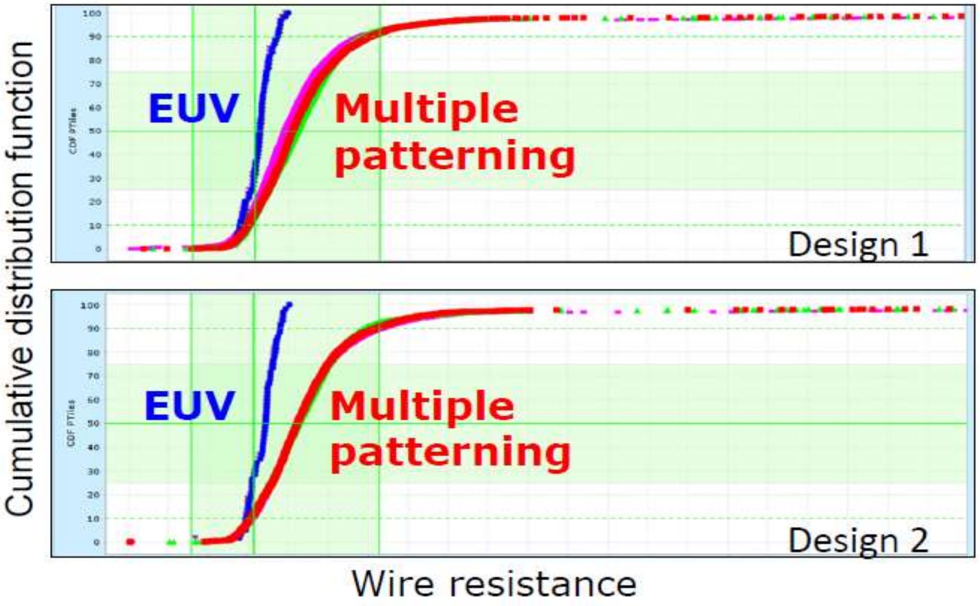


Node	28nm	20nm	10nm	7 nm all immersion	7 nm all EUV
# of lithography steps	4	8	11	33	9
# OVL metrology	4	10-11	14-17	?	12
Max metrology / litho steps	1	2	3	3	2

EUV litho improves metal interconnect resistance

EUV vs Multiple Patterning: variation

Cumulative distribution of Interconnect Resistance



- Electric test data: EUV single exposure patterning has tighter distribution compared to ArFi multi-patterning

Results from 10 nm technology learning vehicle

J. Shearer, (IBM), AVS 2014

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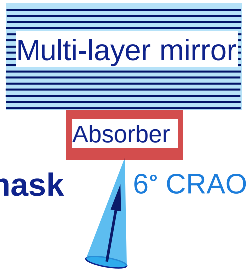
EUV modeling challenges addressed by Tachyon NXE

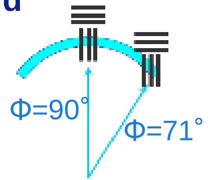
NXE scanner



mask

projection optics

field



Modeling challenges

Oblique Incidence
(Chief Ray Angle at Object)

3D Mask Topology
(absorber on ML mirror)

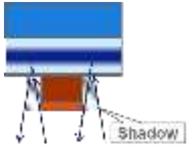
Arc-shaped field
(Chief ray phi)

Residual mirror roughness

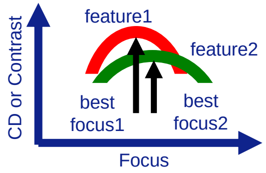
Effects are pattern & slit position dependent:
NXE SMO & full field OPC is required

Imaging impact

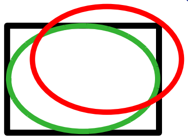
HV print bias
(shadowing effect)



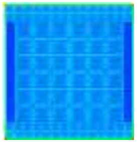
Best focus shift and Bossung tilt



Pattern shift
non-telecentricity
(impacting overlay)

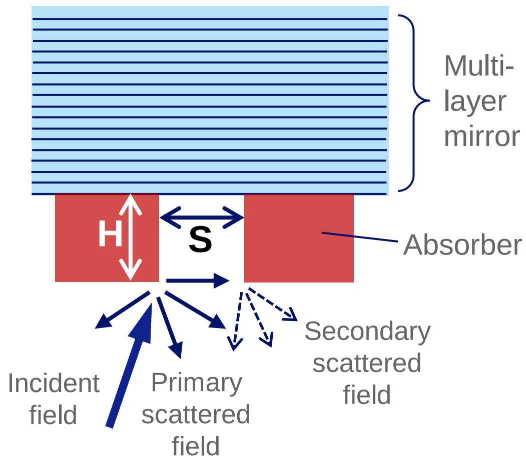


Flare
(pattern/slit dep.)



3D Mask model enhancement for EUV applications

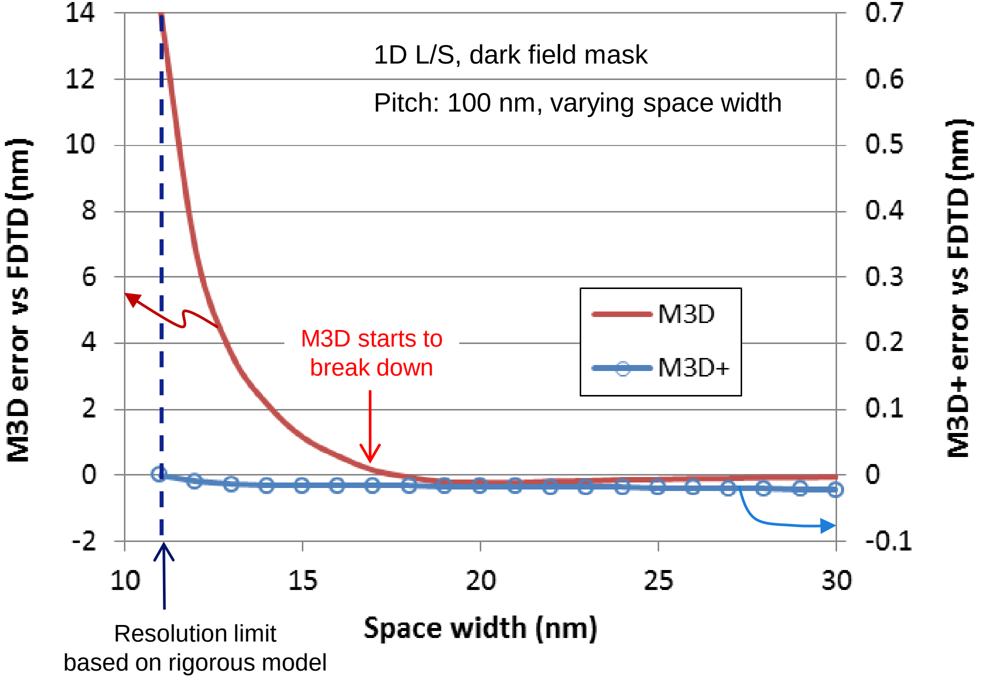
New Tachyon NXE M3D+ model captures the edge-to-edge interaction



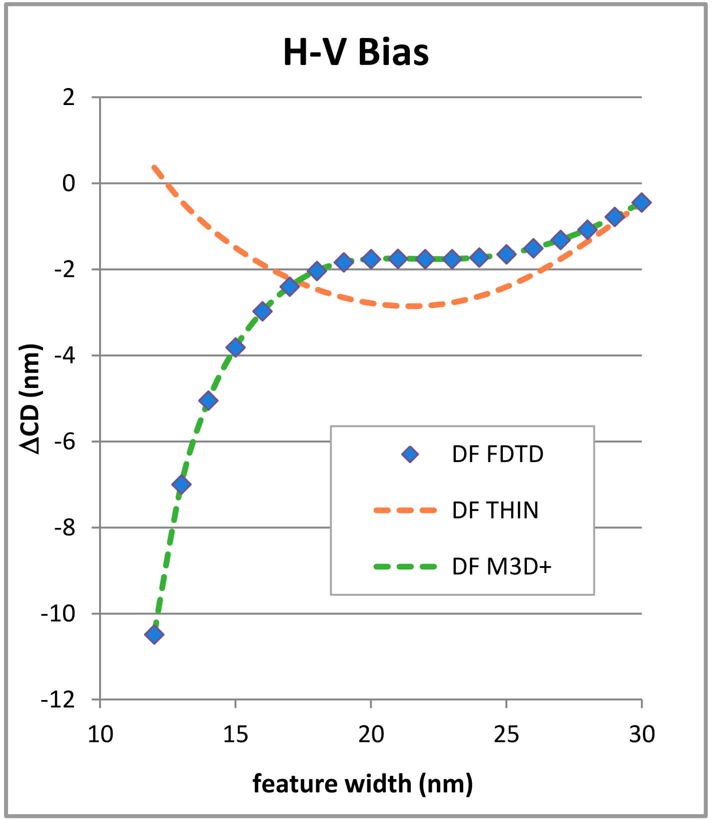
- EUV mask is more susceptible to secondary scattering
  - H >> wavelength
  - S ~ H for dense patterns
  - Reflective mask

M3D+ vs M3D Comparison

Conventional M3D model accuracy breaks down at tighter spaces

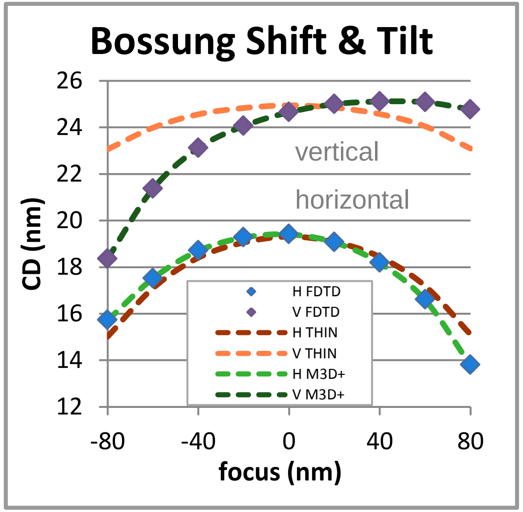


NXE M3D+ enables accurate and fast EUV simulation

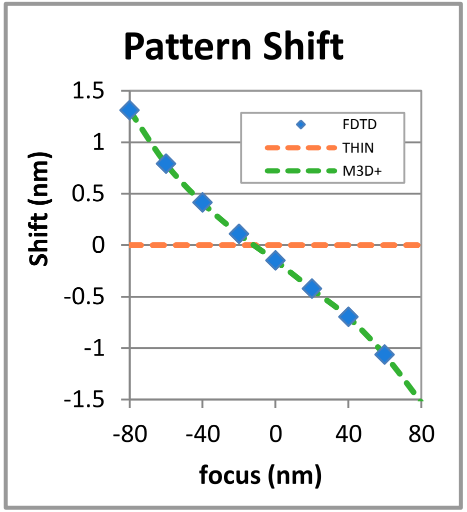


1D L/S, pitch: 100 nm, slit edge

- Rigorous model (FDTD) used as reference
- Thin-mask model is fast but fails at smaller feature sizes
- Tachyon NXE M3D+ is fast and matches rigorous model
- Conclusion holds for HV bias, Bossung tilt, best focus shift , and for pattern shift



Bright field, 1D L/S, slit edge pitch: 100 nm, width: 17 nm

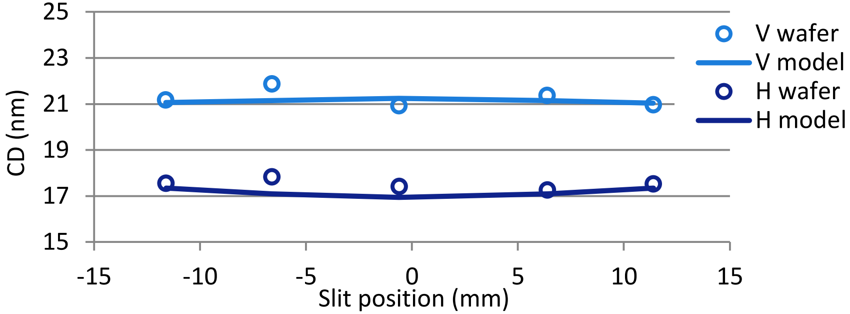


Dark field, horizontal L/S, slit edge pitch: 100 nm, width: 17 nm

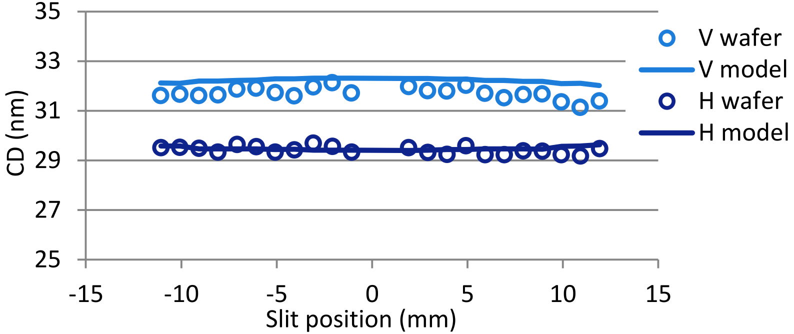
Model accurately predicts CD through-slit

- NXE 3300 IMEC 10 nm node metal layer calibration reticle
- NXE M3D+ model calibrated with 1D and 2D test patterns
- “Model-based” shadowing capability

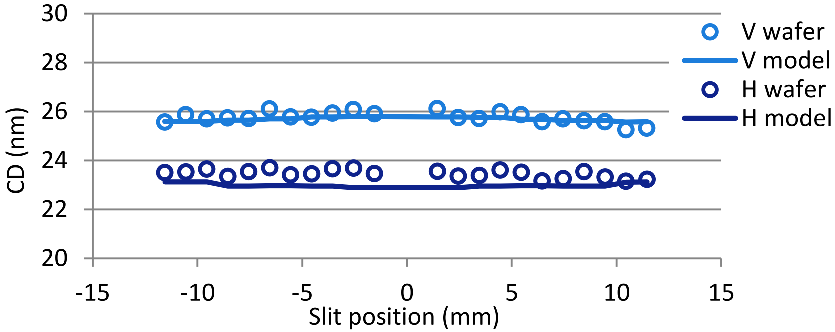
Pitch 48 CD 21 RMS: 0.40 nm



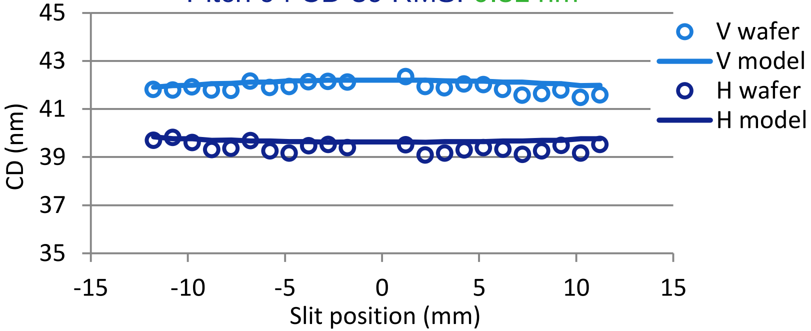
Pitch 50 CD 29 RMS: 0.40 nm



Pitch 48 CD 24 RMS: 0.38 nm



Pitch 94 CD 39 RMS: 0.31 nm



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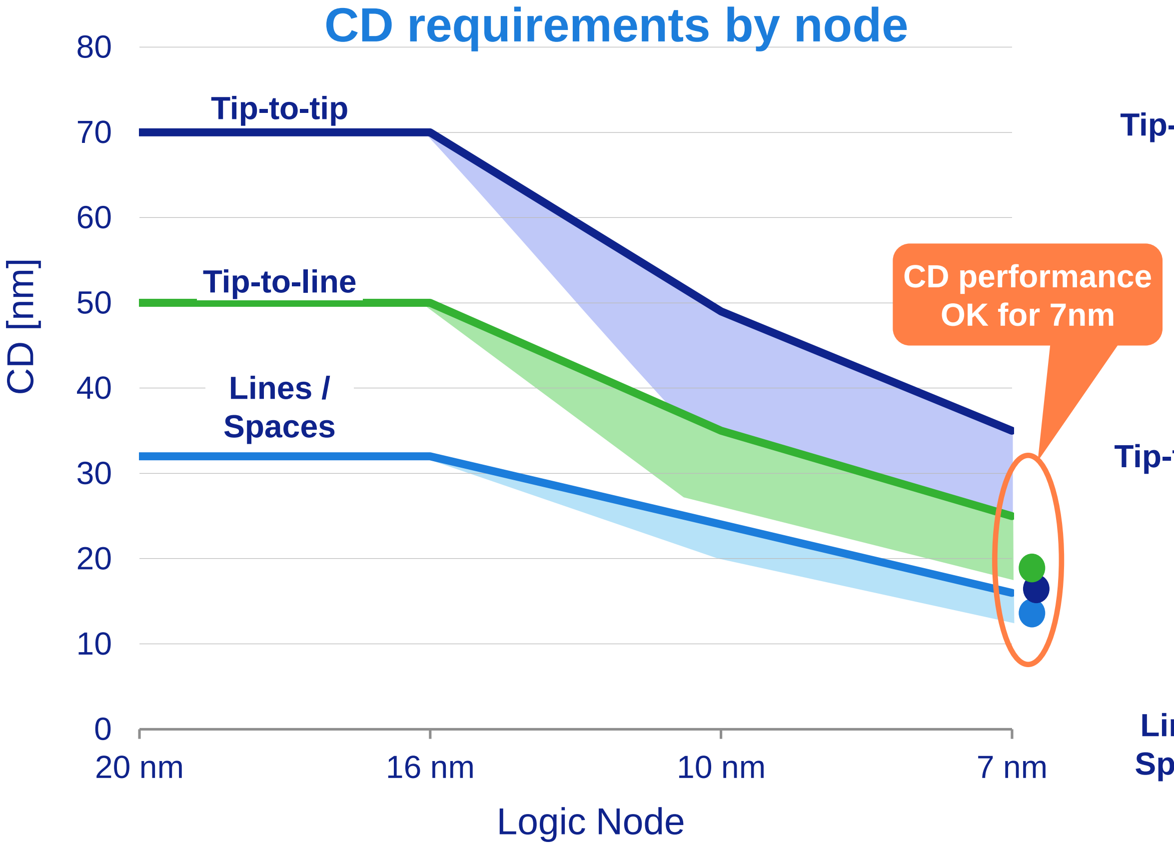
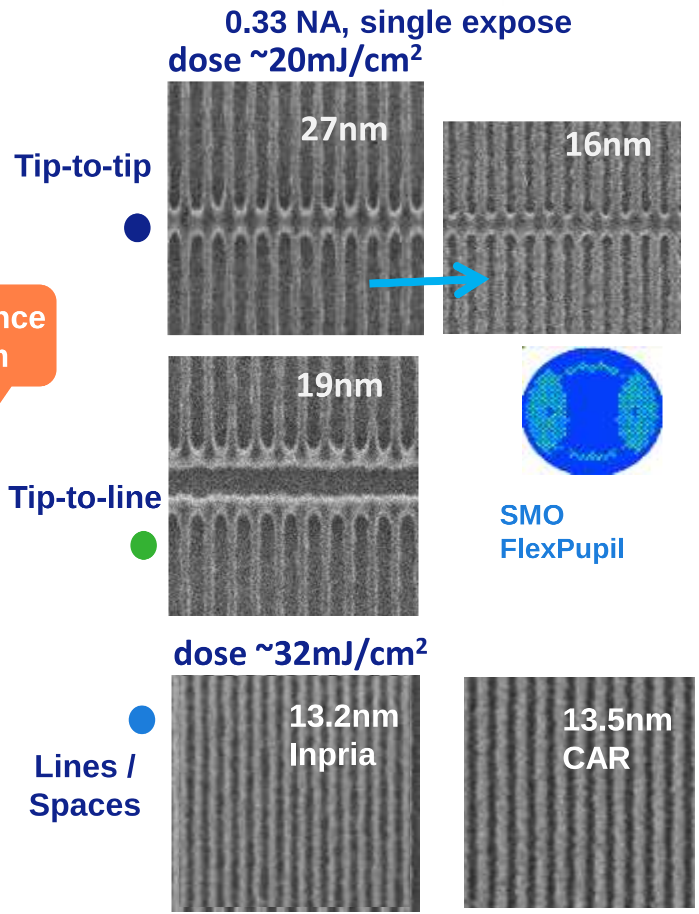
EUV Imaging Performance meets 10 & 7nm node requirements
Tachyon SMO optimized FlexPupil improves Resolution





NXE illumination options roadmap

SMO optimizes FlexPupil enabling advanced EUV imaging

2013 2014 2015 2016 2017

NXE:3300B

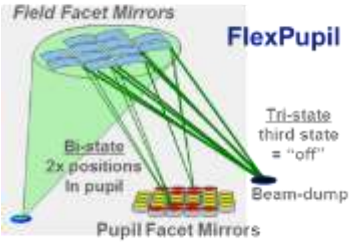
- *Conventional illumination*
- *Off-axis illumination option (6 pre-selected settings)*

NXE:3300B *FlexPupil option (custom illumination)*

Possible field HW upgrade

NXE:3350B *FlexPupil* | *3400 illuminator*

NXE:3400B* *3400 illuminator*



NXE SMO optimizes FlexPupil

Increasing EUV imaging requirements

Pattern placement aware SMO reduces non-telecentricity

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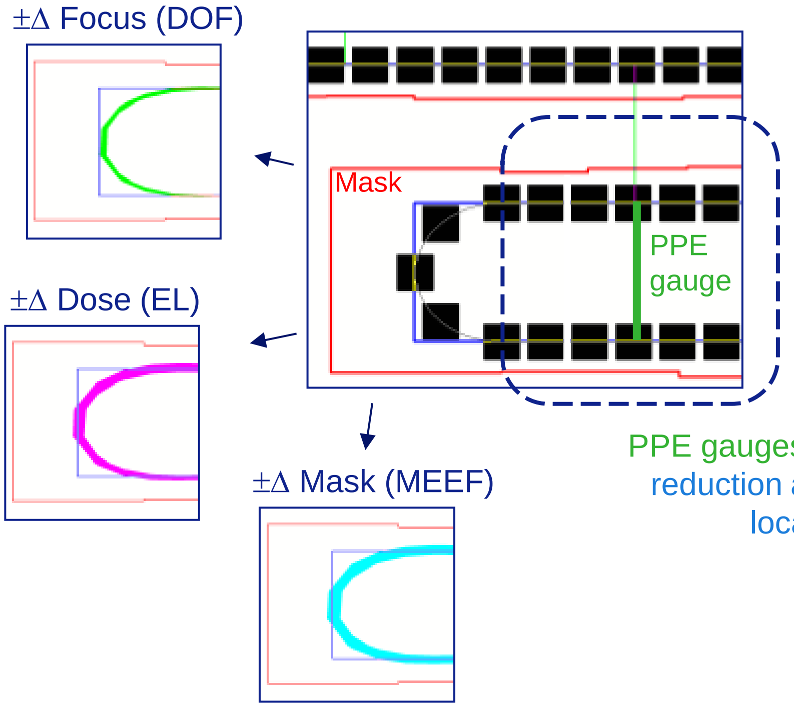
Standard cost function EPE* evaluated through process variations

$$\mathrm{CF} = \sum_{\mathrm{pw,e}} w_{pw,e} EPE^{p}$$

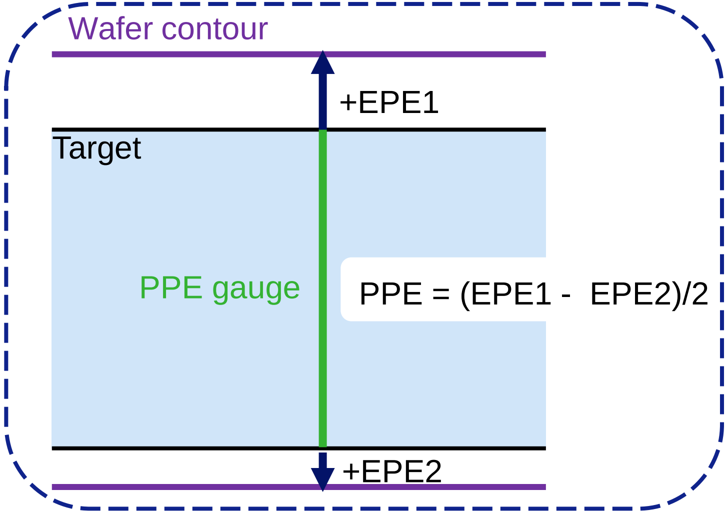


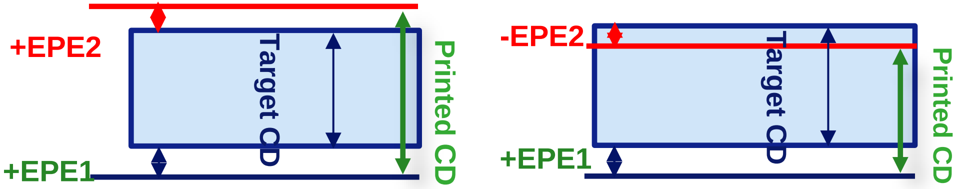
+

PPE gauges enable PPE reduction at a specific location

Placement-aware cost function PPE* evaluated at PPE gauges

$$\mathrm{CF} = \sum_{\mathrm{pw,e}} w_{pw,e} (EPE^{p} + w\ PPE^{p})$$





*EPE: Edge placement error *PPE: Pattern placement error

Placement-aware SMO improves total process window

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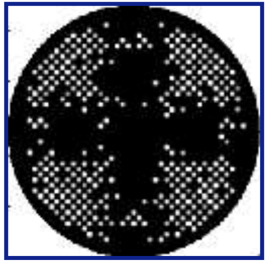
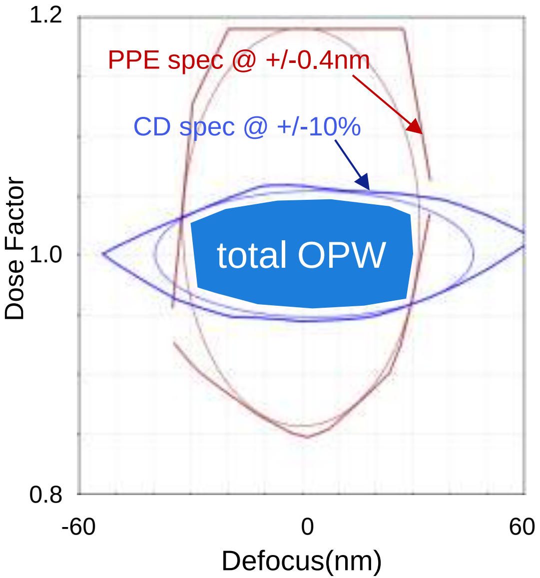
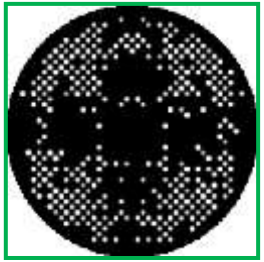
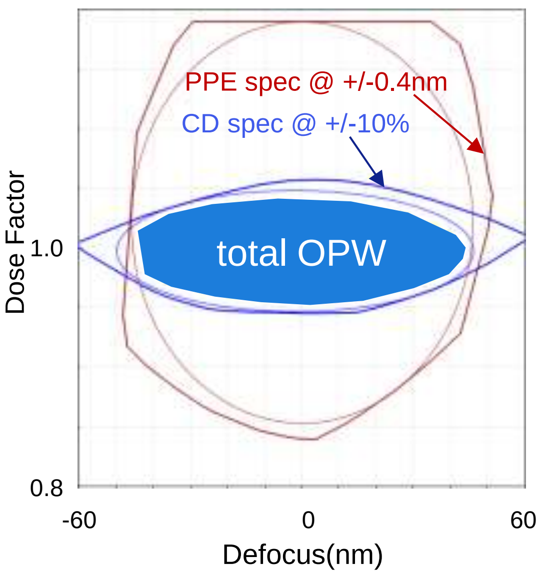
SMO: EPE only



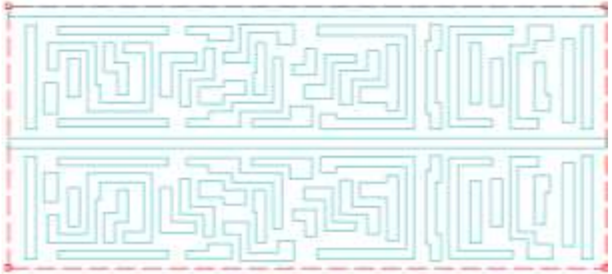


SMO: EPE + PPE





7 nm node logic metal-1 case



Process window DOF@10%EL	EPE only	EPE + PPE
CD based	90	97
PPE based	65	97
CD and PPE combined	**65**	**95**

45% improvement

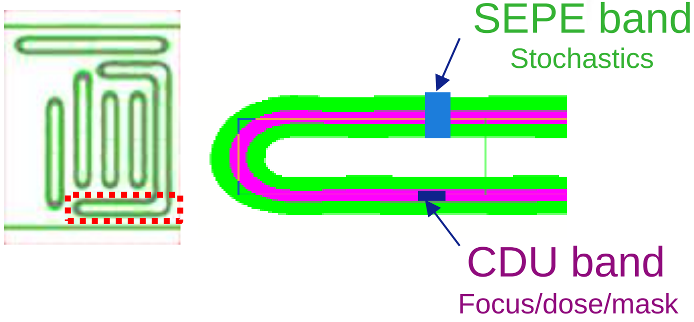
EPE = Edge placement error
PPE = Pattern placement error

SMO can optimize ILS to reduce LER

Factors impacting LER:

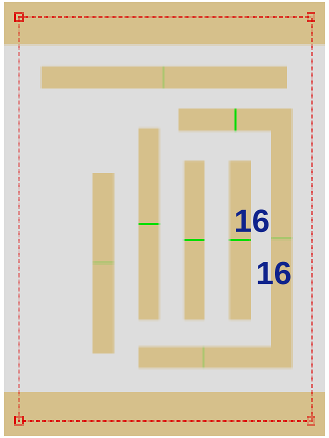
- Statistical local variation of absorbed photons
- Acid diffusion length
- Image log slope
- Dose (anchor mask bias)
- Target (litho) bias

Focus of SMO application

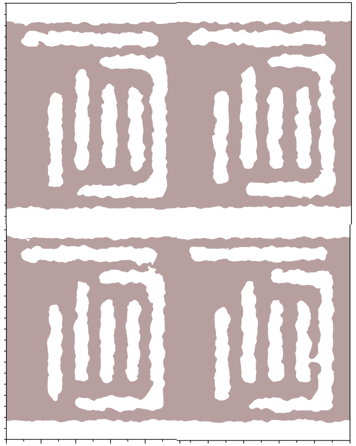


L7 metal-1 logic design

- CD=16nm, pitch=32nm, k1=0.39
- NXE:3350B, NA=0.33



Physical stochastic resist model contours or wafer data

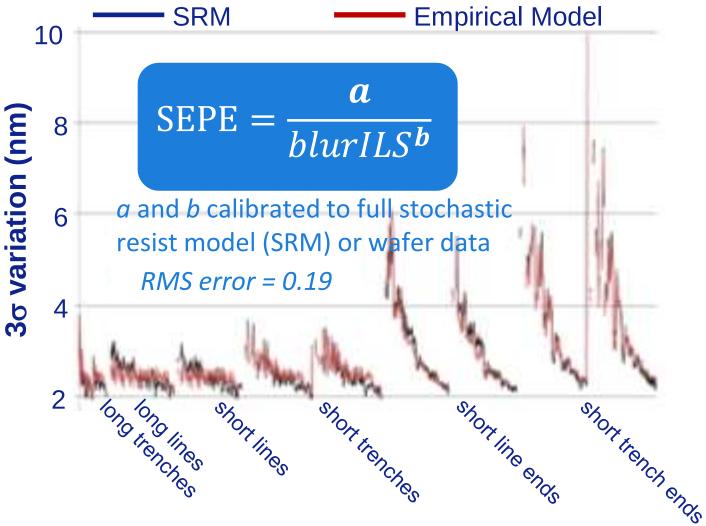


Stochastic edge placement error (SEPE)

$$\text{SEPE} = \frac{a}{blurILS^{b}}$$

a and *b* calibrated to full stochastic resist model (SRM) or wafer data

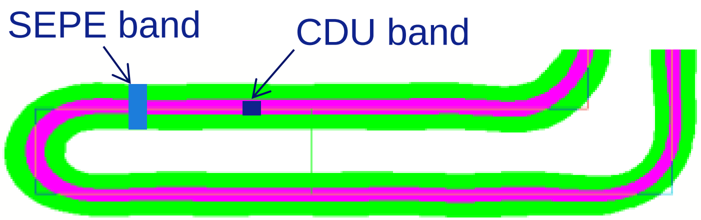
RMS error = 0.19



SMO SEPE band reduction results

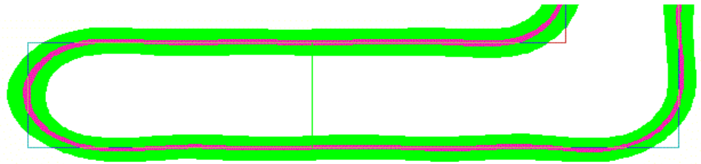
NXE:3350 FlexPupil optimization

Pupil & mask optimization



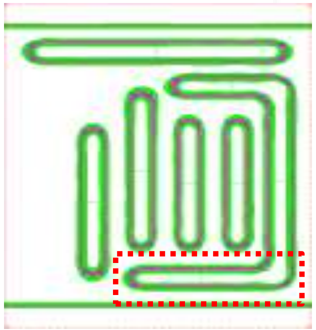
SEPE = 4.0 nm

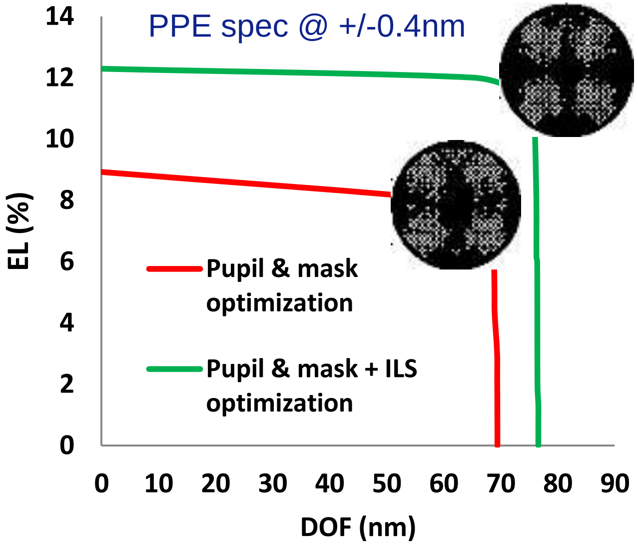
Pupil & mask optimization with
- *Improves ILS*
- *Optimal dose & target bias*



SEPE = 3.0 nm

25% SEPE reduction





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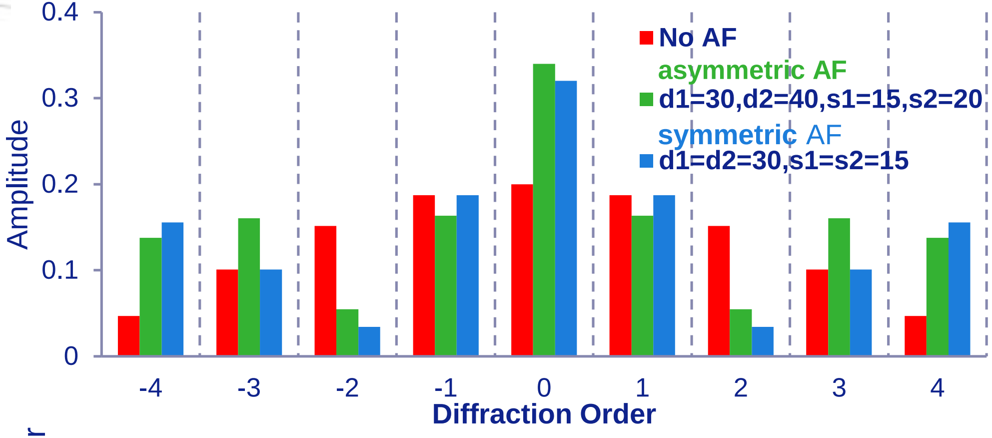
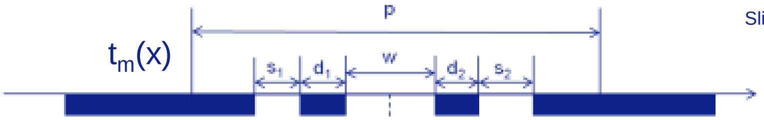
Asym. SRAF can be used to reduce Bossung tilt & shift





$T_m(f_x)$ electric field of the diffraction pattern

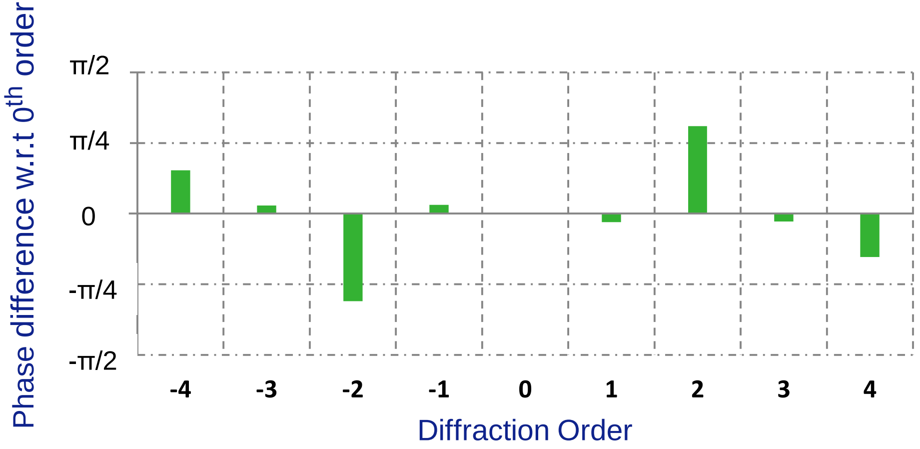
$T_m(f_x) = F\ \{E_i(x)\cdot t_m(x)\}$

$E_i(x)$: incident electric field.

$t_m(x)$: mask field transmittance functions

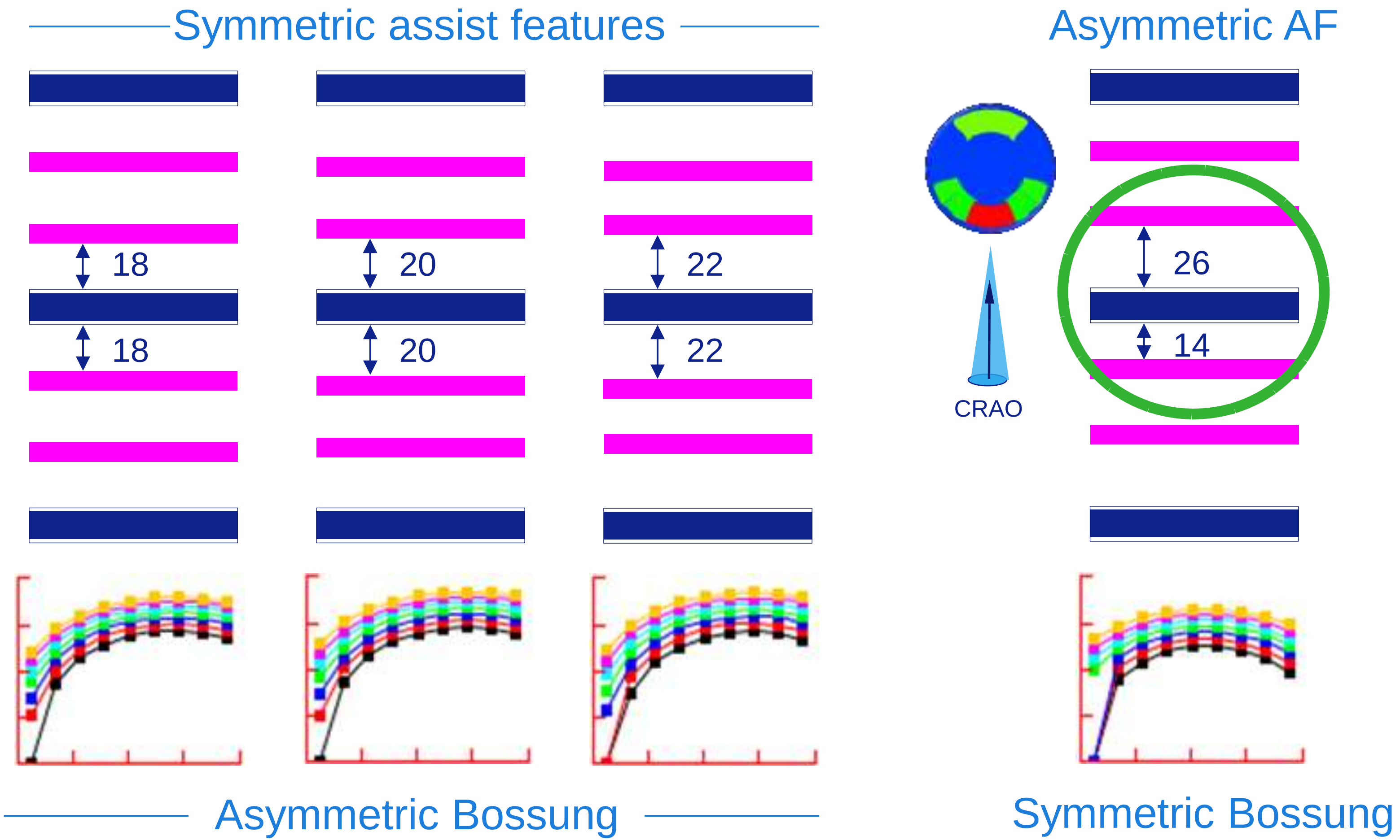
symmetric AF: $T_m(f_x) = R(f_x)$

asymmetric AF: $T_{m(f_x)} = R(f_x) + iI(f_x)$

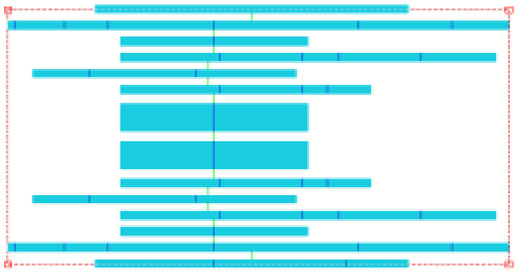


- Assist feature enhances the higher diffraction orders amplitude: ***improves contrast***
- Asymmetric AF introduces phase shift between 0^{th} and higher orders: ***balances m3d phase effect***
- Advantages: ***Local effect, Full-chip solution***

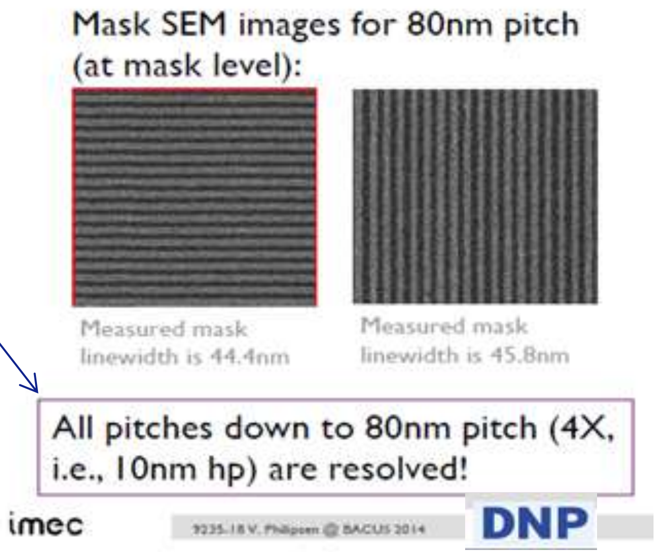
Asymmetric assist features reduce Bossung tilt



SMO optimizes FlexPupil and asymmetric SRAF



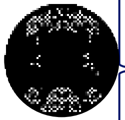
- L7 metal 2 like design
  - Min CD: 15 nm, min pitch: 30 nm
  - Other pitches: 60/90/175 nm
- NXE 3300B, NA = 0.33
- k_1 = 0.37
- Assist feature width = 10 nm



L7 design → SMO without AF

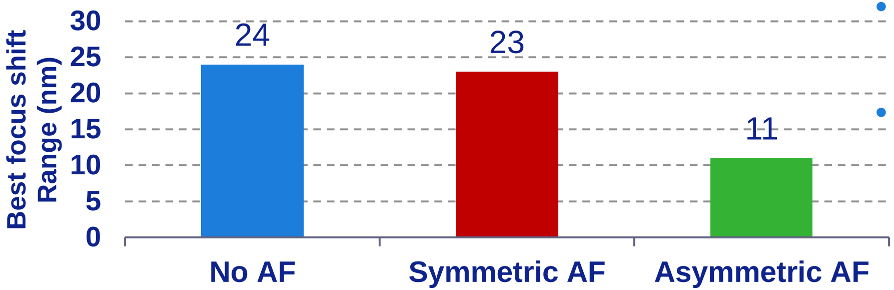
SMO without AF → (Optimized pupil from SMO) → OPC with symmetric AF

SMO without AF → (Optimized pupil from SMO) → OPC with asymmetric AF

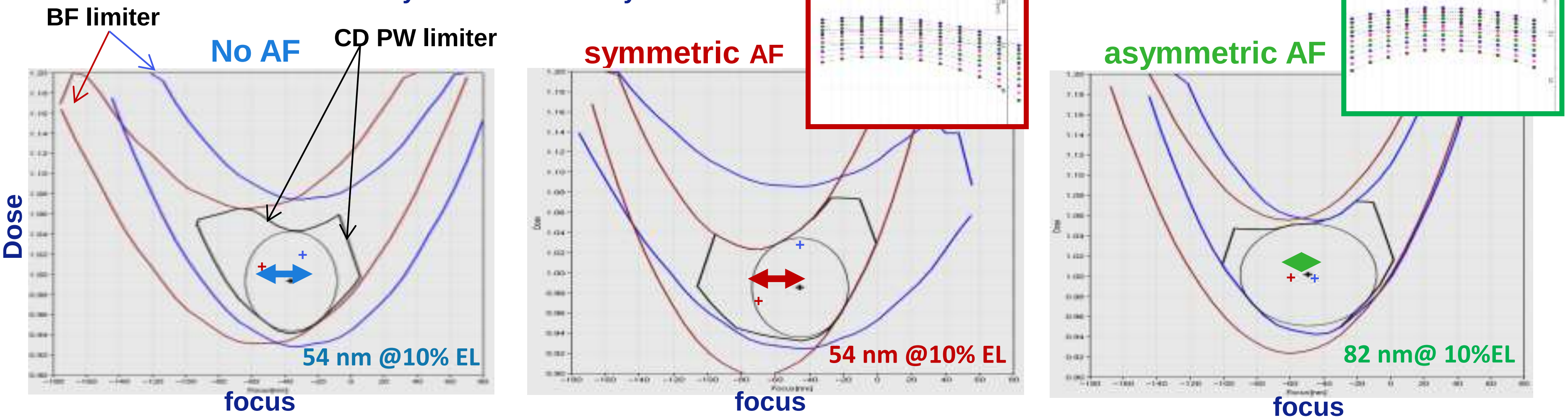


Compare:
- OPW
- PW limiters
- best focus range

Asymmetric AFs improve OPW by correcting Bossung tilt



- Without assist features (AF), large best focus range and poor contrast limits overlapped process window (OPW)
- Symmetric AFs improve contrast, but cannot correct best focus shift and introduce Bossung tilt limits OPW
- Asymmetric AFs reduce best focus shift (-54%), correct Bossung tilt, and increase OPW (DOF @ 10% EL increases by 51%)



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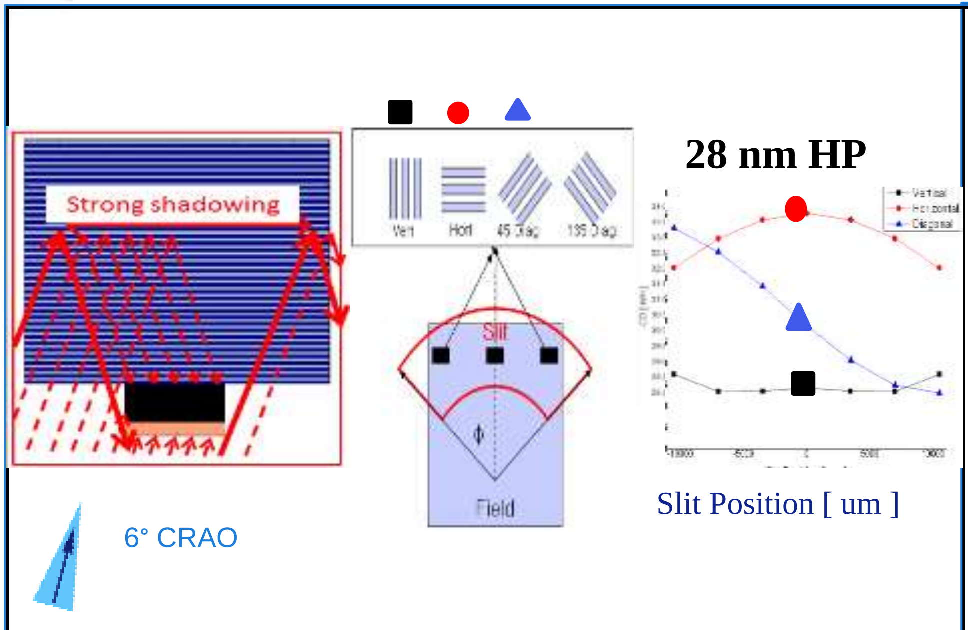
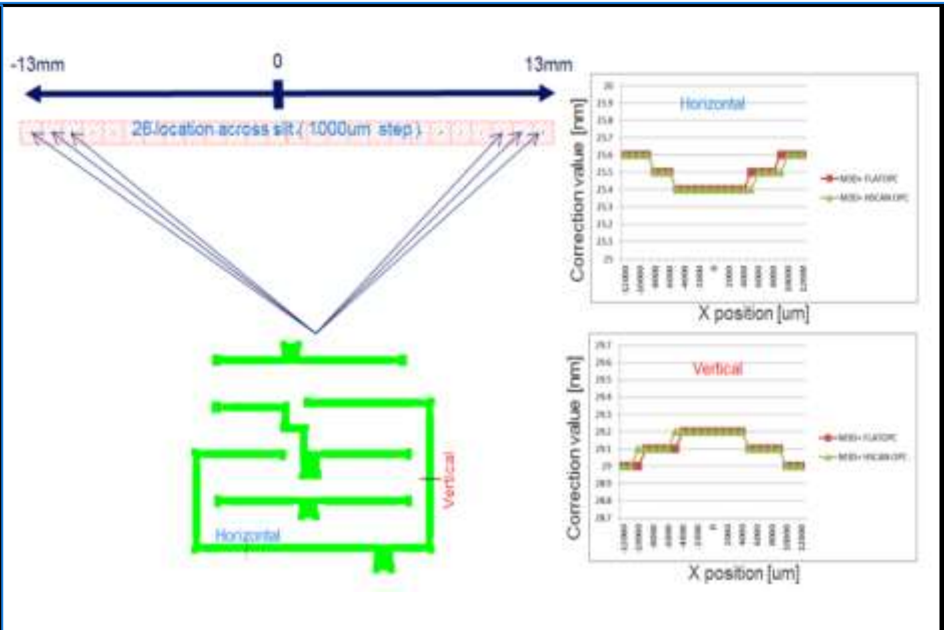
Full field OPC needed to compensate Shadow effect

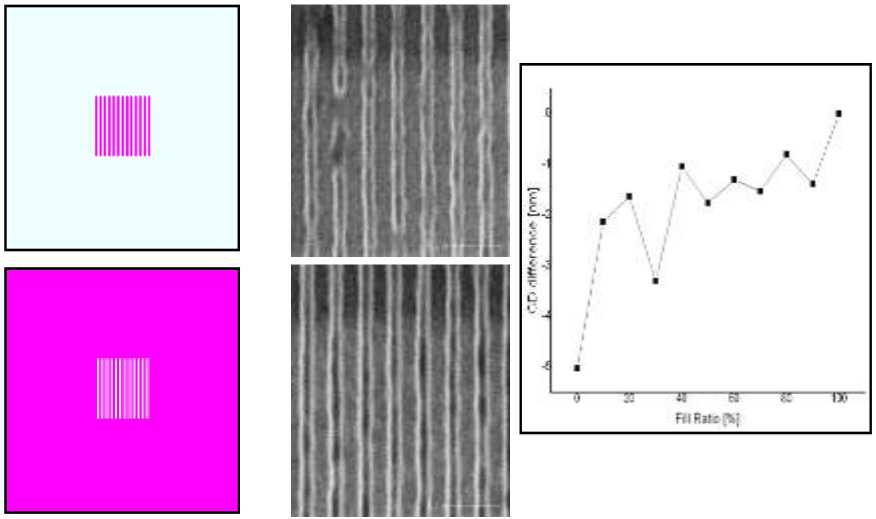




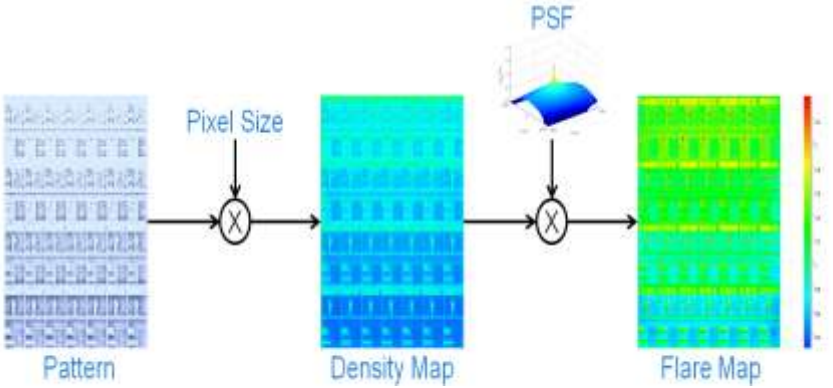
Shadowing: CD difference caused by 6 degree Incident angle on mask for patterns of different directions and slit position	Both Model Based(M3D+) and Rule Based Shadowing(Cosine2) Correction is availabile

- Shadow effect is long range with slit location dependency → requires full field correction
- Slit specific OPC required → need more computation resources and larger data storage

Full field OPC required to compensate Flare



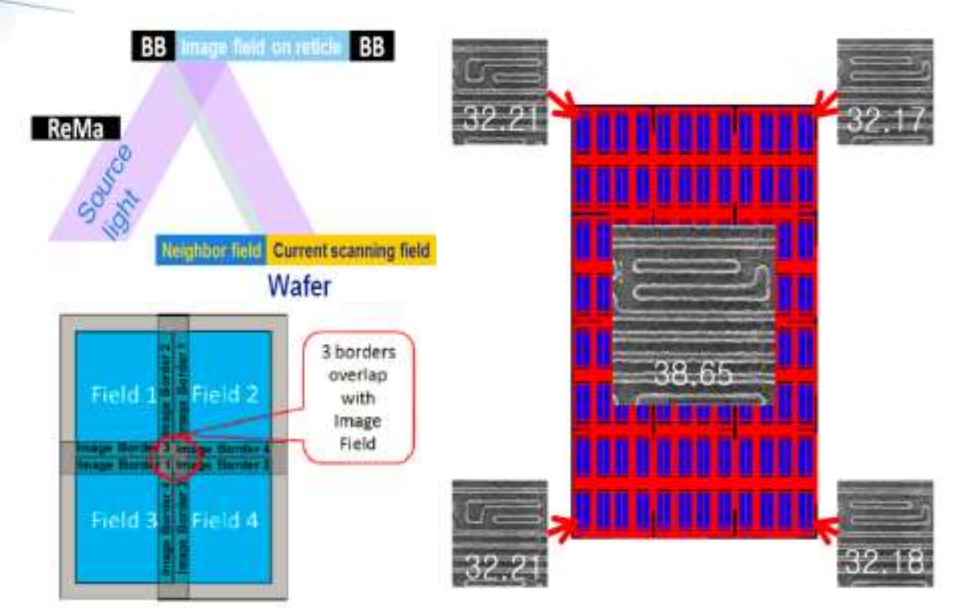
Flare: CD difference caused by combination of stray light and pattern density on mask



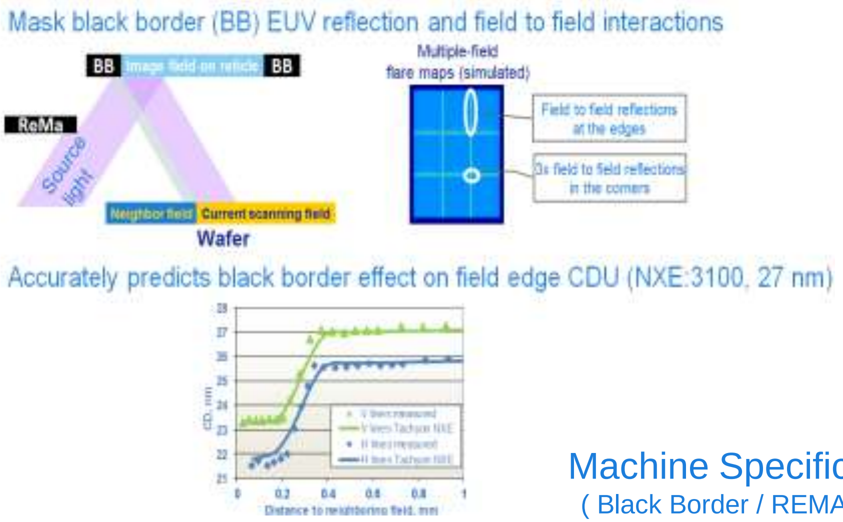
Flare Mapping and OPC correction based on Flaremaping

- Flare has a very long range effect and location dependency→ requires full field correction
- Slit position specific OPC required → need more computation resources and larger data storage

Full field OPC required to compensate Black Border



Black Border and Rema: CD difference caused by stray light from REMA and Black Border of Mask



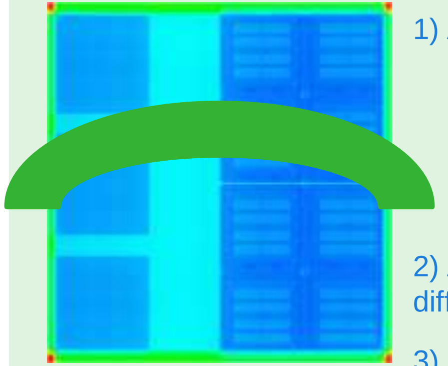
Machine Specifics
(Black Border / REMA)

Address Black Border and Rema reflectance in flaremapping for OPC correction

- Black Border effect is long range → requires full field correction
- OPC can correct the Black Border introduced CD error

Tachyon NXE HScan solution addresses computation and memory challenges in full field OPC

HScan Functions



HScan:

1) Analyze GDS Hierarchy based on

(1) flare amount

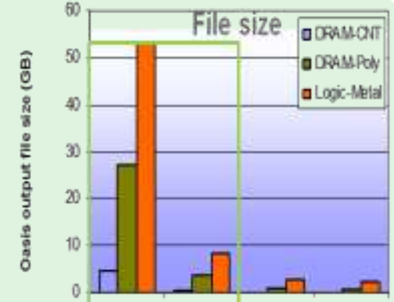
(2) Slit position (shadowing)

2) Analyzed result is used to group different cells together

3) OPC is ran for each different cell, then result is pasted to minimize runtime

HScan reduces runtime and output file size

DRAM-CNT	60.72	0.83	0.78	0.68
DRAM-Poly	103.75	2.75	1.38	1.15
Logic-Metal	60.77	6.67	3.13	3.12
Correction	Flat	HScan	HScan	HScan
Optical proximity	✓	✓	✓	✓
Flare	✓	✓	✓	✓
Mask shadowing	✓	✓	✓	x
Mask black border	✓	✓	x	x

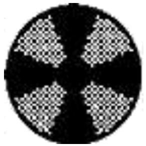


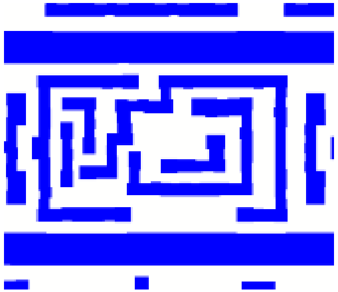
DRAM-CNT	4.70	0.40	0.13	0.13
DRAM-Poly	27.30	3.80	1.10	0.55
Logic-Metal	53.00	8.40	2.60	2.30
Correction	Flat	HScan	HScan	HScan
Optical proximity	✓	✓	✓	✓
Flare	✓	✓	✓	✓
Mask shadowing	✓	✓	✓	x
Mask black border	✓	✓	x	x

HScan shows significant improvements in runtime (10x~70x) as well as output data size (10x) for both logic and memory devices

Tachyon NXE OPC with M3D+ model enables robust imaging with large process window

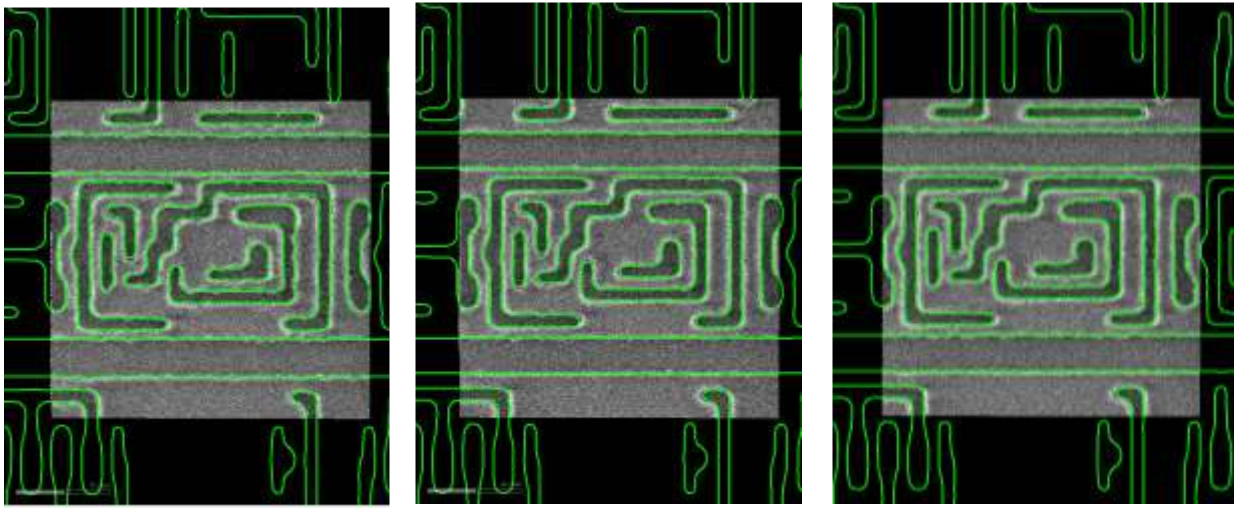
- IMEC N10 metal-1 logic cell: NXE:3300B exposure, Quasar45
- Mask tape-out using Tachyon NXE OPC with M3D+ model
- Predicted contours (green) match well SEM contours





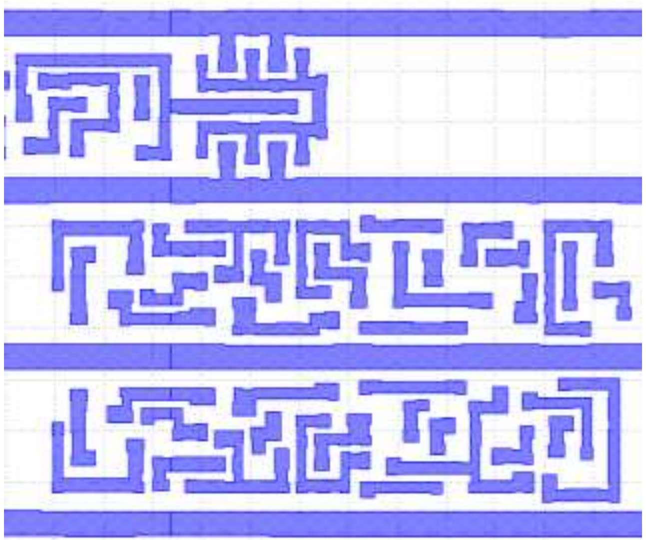
Tachyon NXE OPCed mask
white is absorber

Focus: -80 nm Focus: 0 nm Focus: +80 nm

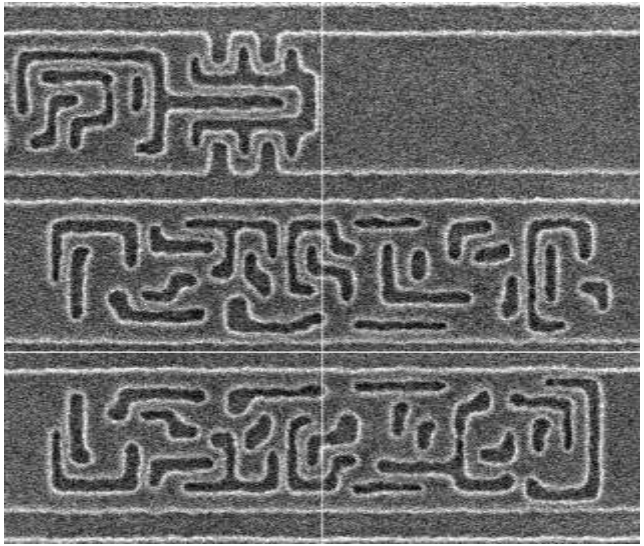


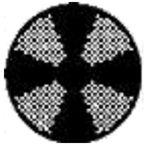
Logic 7 nm node early results: Mask taped out using Tachyon NXE OPC and exposed on NXE:3300

- Good L7 M1 logic cell imaging results
- Fully routed 2D non-gridded M1 logic cell 18 nm trench CD, 36nm pitch



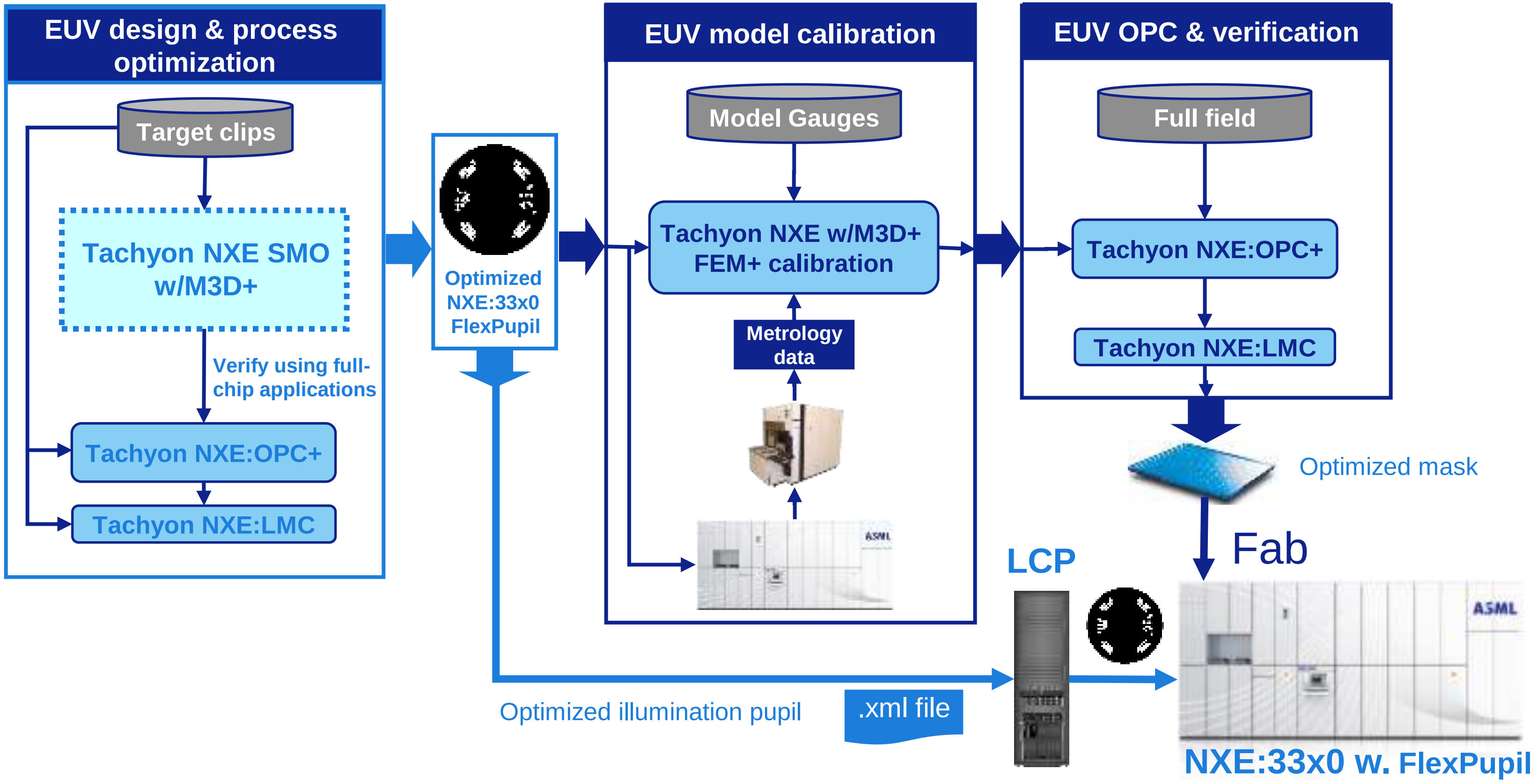
White is absorber
Blue is multilayer (mirror)





Illumination

Tachyon NXE SMO and OPC optimize scanner and mask for best full field process window



Agenda

- Introduction: Need for EUVL for sub-10 nm node
- Modeling challenges for EUV specific effects
- FlexPupil and Source-mask optimization (SMO)
- EUV sub-resolution assist features (SRAF)
- Full field OPC and verification
- Summary

Summary

- ASML/Brion has developed solutions to accurately model various EUV specific effects
- NXE SMO optimizes FlexPupil to minimize the pattern placement error through defocus for best placement aware process window
- Developed compact LER model to evaluate the stochastic edge placement error (SEPE) and NXE SMO to optimize Flexpupil to enhance image log slope to reduce stochastic effect
- Optimize asymmetric assist feature placements to enlarge common process window, reduce Bossung tilt and minimize best focus shift
- Full field RET and OPC solutions are validated and ready for EUV lithography deployment below 10 nm

Thank you for your attention!